5. New Design

This section describes the consideration of life-cycle environmental factors in the development, and testing of original/first-time products, systems, processes, or facilities. A chemical manufacturing case study example is included to illustrate how the elements of the life cycle engineering framework apply to these types of decisions.

5.1 Products and Systems

New products and systems have one characteristic that distinguishes them from upgrades or maintenance – degree of evaluation team knowledge of the product or system attributes. Whereas most upgrades or maintenance procedure decisions involve an assessment of how commercial technologies will best be suited for improving existing products and system, knowledge of the environmental, cost, and performance characteristics of new products and systems will be by definition limited. New products and systems are by nature subject to greater uncertainty in their life cycle engineering characterization. This higher degree of uncertainty needs to be acknowledged and accounted for by the evaluation team.

5.2 Processes and Facilities

The development of new processes shares much of the uncertainties associated with new products and systems development. The lack of a full understanding of the performance, cost, and environmental characteristics means that the team will need to return to the analysis periodically and reevaluate their conclusions as data about the process become better known. One way to address this uncertainty would be to delay completion of the detailed step of the assessment until later in the development process realizing that the flexibility to modify the process may be more constrained. New facility development has fewer uncertainties associated with the physical structure since even in the case of novel features, such as lighting, power, and space conditioning, much of the technology will be choosing among commercialized options. However, new facilities development also brings in elements associated with environmental assessment of siting alternatives and the related issue of due diligence in assuring environmental sensitivity of the site development process.

5.3 LCE Case Study: BDO Process Development

1,4-Butanediol (BDO) is a widely used chemical building block for numerous commercial chemical and polymeric compounds. Conventional processes for the synthesis of BDO use petrochemical feedstocks for their starting materials. About 90% of 1995 domestic production used the Reppe process in which acetylene and formaldehyde are reacted to produce 1,4-butenediol. This intermediate is then hydrogenated to produce BDO. An alternative process was sought to produce BDO via a route not dependent on traditional feedstocks.

5.3.1 Targeting the Evaluation

Establishing the Function being Provided

The function of the new process is to produce a unit quantity of BDO using non-conventional feedstocks at a cost below the current production cost of BDO produced by conventional synthesis routes. Note that the functional specifications for the process do not dictate a purity level for the produced BDO. Rather, the downstream use of the material will determine how much impurity is tolerable and how the primary manufacturing process needs to accommodate the required purity levels.

Naming an Evaluation Team

The evaluation team for this effort consisted of several distinct groups. Members of the team included:

- U.S. Department of Energy, Alternative Feedstocks Program staff who oversaw the development team and provided an integration perspective on balancing of environmental versus other goals.
- Environmental specialists whose responsibility was to identify the characteristics of the conventional BDO manufacturing system that had the potential to create adverse environmental impacts and to analyze the impact potential profile of an alternative process.
- Process chemistry and engineering developers who were involved in laboratory and pilot scale process design experiments against a set of well-defined criteria.
- Process cost analysts who were responsible for estimating the costs of the operations involved in the alternative process.
- Life cycle process engineers who were responsible for establishing the system boundaries, identifying and collecting process information on the upstream materials production, and characterizing the waste management aspects of the coatings operation. This group also had the task of making recommendations back to the process engineering team to incorporate improvements into the next generation design.

These groups interacted on a number of occasions, but could not function as an entirely integrated team. The latter four groups formed the primary LCE team.

Developing Requirements and Goals

Initial requirements for the new process consisted of a combination of performance, cost, and renewable feedstock attributes. Details on these requirements (R) and goals (G) may be found in Table 5.1, which is an excerpt of *Routine and Unanticipated Maintenance Worksheet 1*. The initial set of aspects were largely confined to the manufacturing life cycle stage, although parameters such as feedstock cost and availability are associated the upstream stages as well as the in-house activities. These initial requirements were not developed with a life cycle engineering framework in place.

Table 5.1 New BDO Process Requirements and Goals

Category	Applicable Life Cycle Stage				Requirements and Goals	Requirement (R) or Goal (G)
	MP	MC	USM	D		
Performance						
Chemical			X		Fermentation step yields must meet targets for purification stage	R
Chemical			X		Acceptable product quality as defined by purchaser specifications	R
Cost						
Materials			X		Lower cost for feedstock and process chemicals	R
Materials and Equipment			X		Production cost substantially below current estimated cost	R
Materials			X		Reduced labor costs compared with baseline	G
Environmental – Facility						
Hazmat management and waste			X	X	Reduce or eliminate generation of waste solvents and sludges	G
Energy consumption	X	X	X		Less than baseline	R
Environmental – Local						
Photochemical smog production	X	X	X		Reduce emissions compared with conventional process	R
Water pollution			X		Minimize solvent and nutrient discharges to surface or groundwater	G
Toxic materials in the environment	X	X	X	X	Minimize solvent and biosolids releases	R
Landfill space		X	X	X	Decrease solid waste generation	G
Environmental – Regional						
Visibility impairment			X		Reduce the amount of particulates released	G
Environmental- Global						
Resource conservation	X	X	X	X	Reduce fuels consumption and use renewable resources	R

Proposing Engineering Technologies and Options

During the course of developing the process flowsheet that was ultimately used for the environmental assessment, the engineering team assessed and modified the technologies for synthesizing and purifying the product of the alternative synthesis route several times. These technology options included alternative fermentation reactor configurations, several sets of purification process steps and multiple options for co-product and waste processing prior to recycling or disposal. In all instances these options were rejected on the grounds that they failed to meet the performance and cost targets and therefore any environmental requirement or goal assessment was moot. However, in an ideal deployment of the LCE approach, those initial options would have at least had some preliminary assessment for their environmental attributes to complement the performance and cost analyses.

5.3.2 Preliminary Assessment

Defining the Technology Life Cycles

Figure 5.1a through c shows the life cycle activities and material/energy flows associated with each of the technologies. This analysis boundary is similar to that shown previously for the CARC example. In this case the downstream boundary for the new process analysis is the manufacturing of a unit quantity of BDO. Because the requirements included a statement that the purity be acceptable for the intended use (implying that the alternative process cannot produce inferior product relative to that derived from the conventional technology), the analysis can be streamlined through exclusion of the stages involving the use and disposition of the product. Also, because the criteria span more than the process operation and maintenance life cycle stage, the LCE framework requires the description and consideration of the whole process life cycle.

Figure 5.1a BDO Technology 1: Glucose Fermentation to Succinic Acid

Technology	Technology 1: Glucose Fermentation to Succinic Acid (SA)
Additional material and equipment requirements	• Minor nutrients (HCl, Tryptophan, Cysteine) and process control chemicals (NaOH and CO_2) • Dewatering and biosolids recovery and pre-processing (dewatering) equipment • Fermentation reactor and associated feed and control systems
Operational and maintenance procedures	In accordance with manufacturer's literature and product recipe.

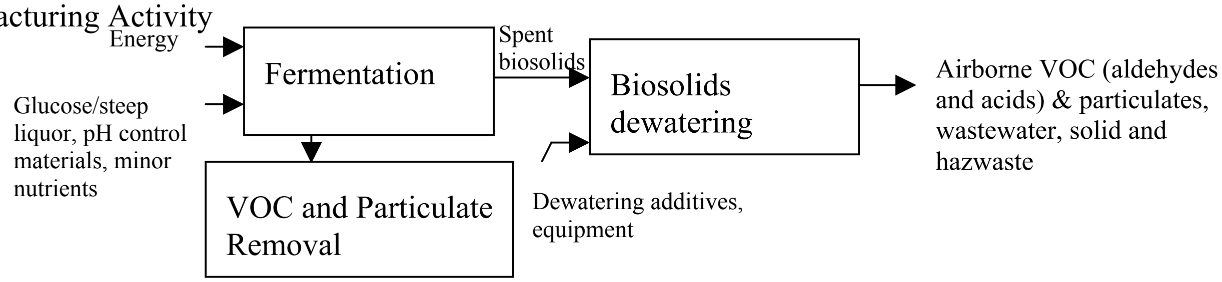
Material Production

Succinic acid is produced through the mediation of bio-engineered microbes. The reactor feed consists of corn-derived glucose and corn steep liquor along with certain micro-nutrients required for the continued viability of the biomass. In addition to the carbon source production steps, material production activities for process control chemicals are included. Excluded are the upstream materials production operations for minor nutrients since these comprise only 2.3% of the total input mass.

Technology Manufacturing

In keeping with typical LCA practice and the streamlined nature of this assessment, the environmental aspects of manufacture of the fermenter and related equipment were not included.

Manufacturing Activity



Material Recovery and Disposal

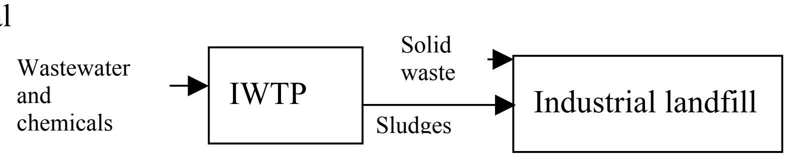


Figure 5.1b BDO Technology 2: Succinic Acid Purification (Electrodialysis)

Technology	Technology 2: Succinic Acid Purification
Additional material and equipment requirements	• Electrolytes and process control chemicals • Coproduct recovery equipment • Electrodialysis cell and associated feed and control systems
Operational and maintenance procedures	In accordance with manufacturer's literature and product recipe.

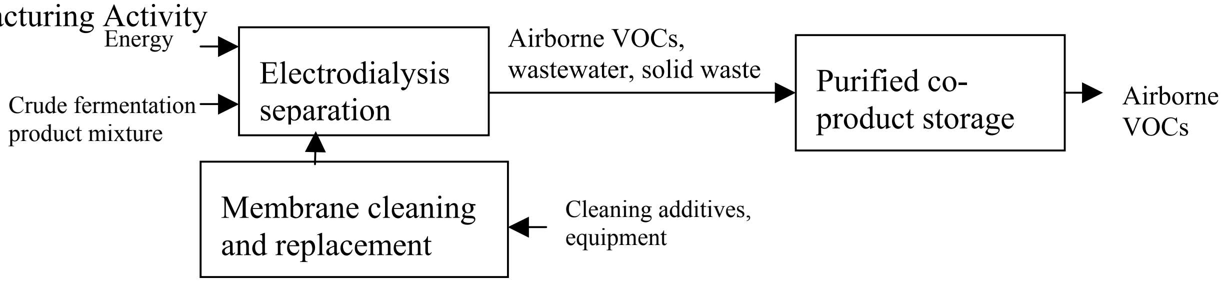
Material Production

Succinic acid produced in the previous step is not pure. It is a co-product along with several other compounds that need to be separated in order for the SA material to be useable for BDO production. One technology for effecting this separation is electrodialysis in which a mixture of materials are placed in a chamber with a semi-permeable membrane forming one of the interior surfaces. Application of an electric field forces certain components of the liquid through the membrane where they are concentrated relative to the original solution. Excluded are the upstream materials production operations for some of the membrane maintenance chemicals since these comprise a small percentage of the total input mass.

Technology Manufacturing

In keeping with typical LCA practice and the streamlined nature of this assessment, the environmental aspects of manufacture of the electrodialysis cell and the membranes were not included.

Manufacturing Activity



Material Recovery and Disposal

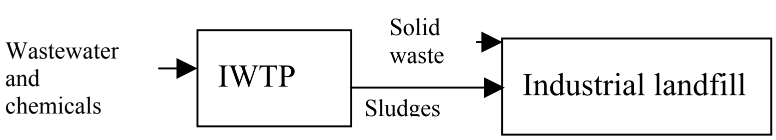


Figure 5.1c BDO Technology 3: Catalytic SA Reduction to BDO

Technology	Technology 3: Catalytic SA Reduction to BDO
Additional material and equipment requirements	• Catalyst • Hydrogen • Reactor and associated equipment
Operational and maintenance procedures	In accordance with manufacturer's literature and product recipe.

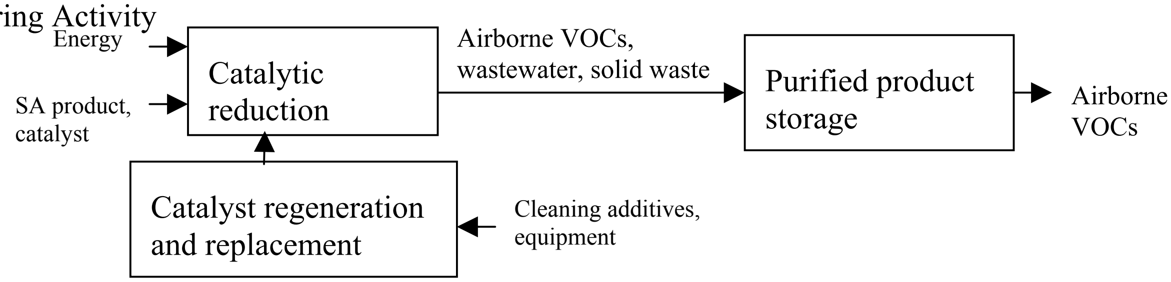
Material Production

The production of hydrogen was included as part of the upstream stages associated with wet milling of corn. Because hydrogenation of oils forms a basic part of the corn processing for many products, it was recommended that the evaluation team not create a stand-alone hydrogenation step as part of the BDO facility. Upstream production of the components of the aluminum oxide catalyst was included.

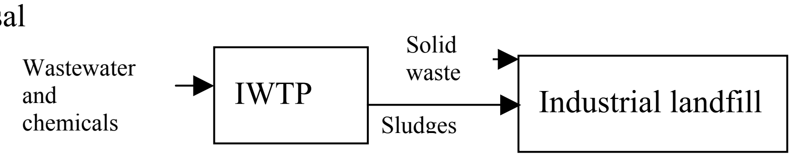
Technology Manufacturing

In keeping with typical LCA practice and the streamlined nature of this assessment, the environmental aspects of manufacture of the reactor and the associated equipment were not included.

Manufacturing Activity



Material Recovery
And Disposal



In this evaluation the choice of technologies was pre-positioned to effect the best current economics of BDO production while satisfying the criterion of using an alternative (non-fossil) feedstock. Therefore, alternative technologies were not identified and a series of preliminary assessments of the degree of achievement of requirements and goals was not prepared, as was the case for CARC. (see Section 3.3.2).

5.3.3 Detailed Assessment

Retargeting the Assessment

The detailed assessment stage consisted of cost and environmental aspects. Performance characteristics were addressed by requiring the product BDO to meet purity levels for use in downstream stages and by the impacts on the production costs of additional separation and purification steps. The economic analyses were based on costs in then current year dollars for firm fixed contract materials procurement from commercial sources. The analysis assumed co-location of the BDO facility at a corn wet mill where the glucose feedstock could be provided with no additional off-site transportation costs. The LCA was based on a functional unit produced at a hypothetical location in the Midwest (Iowa or Illinois).

Environmental requirements and goals were analyzed using a Life Cycle Impact Assessment directed at resource and energy consumption, environmental burdens and waste generation. The environmental evaluation of the selected options consisted of performing a life cycle assessment (LCA) on the technologies outlined above that comprise the alternative production sequence flowsheet in comparison with those associated with the conventional BDO production using the Reppe process. Each analysis consisted of a life cycle inventory to measure the energy and materials flows for the production of selected precursors and BDO. The manufacturing of the capital equipment was not included in this analysis in keeping with standard LCA practice. The downstream boundary was purified BDO ready to ship to customers. Although technology-specific data were available for each of the three steps in the alternative process based on detailed flowsheet modeling using a commercial simulation package, the LCI data were aggregated so as not to disclose certain proprietary pieces of information about the alternative technologies.

Within the primary manufacturing portions of the bio-based BDO life cycle, the data in Table 5.2 indicate that the burden contributions from separation and purification of the crude succinic acid product are significant. In addition, if power is purchased from off-site generation, the contribution to the life cycle profile from electric power generation is dominant. When the overall impacts of the two technologies are compared (Tables 5.3 and 5.4), the intuitive sense that the system based on renewable crop resources is environmentally preferable is seen to be incorrect. The conventional system based on natural gas is the preferred system for 9 of the impact categories. At least in its original design configuration the corn-based system is preferable only on the aspects of resource depletion and carcinogenicity.

LCE results of this type for new systems are appropriately used to develop more refined designs. Based on the analysis of the contributing operations, a number of modifications can be identified (Figure 5.2). For the agricultural portions of the life cycle, use of conservation tillage to reduce soil losses and increase carbon retention will improve the global warming and eutrophication impact scores. Recycling of the fermentation media back to the farm also will improve productivity and may reduce the need for fertilizers slightly. Within the BDO production operations, three improvements were identified. Use of hydrogen produced at the corn wet mill will avoid the cost and environmental burdens associated with building and operating a separate hydrogen plant. Incremental improvements in the electrodialysis system will reduce power consumption and the associated emissions as well as provide a higher purity (and therefore less waste generating) feedstock for the BDO production step.

In addition to improving the environmental profile of the system the LCE analysis identified the potential to better integrate the BDO plant into the surrounding agricultural production activities. Finally, the changes will save a couple of pennies per pound in production costs. This may not seem like very much but, at the projected production scale of 100 million pounds per year, the annual savings amount to more than 2 million dollars.

Figure 5.2 Design Improvements Identified through LCE Process

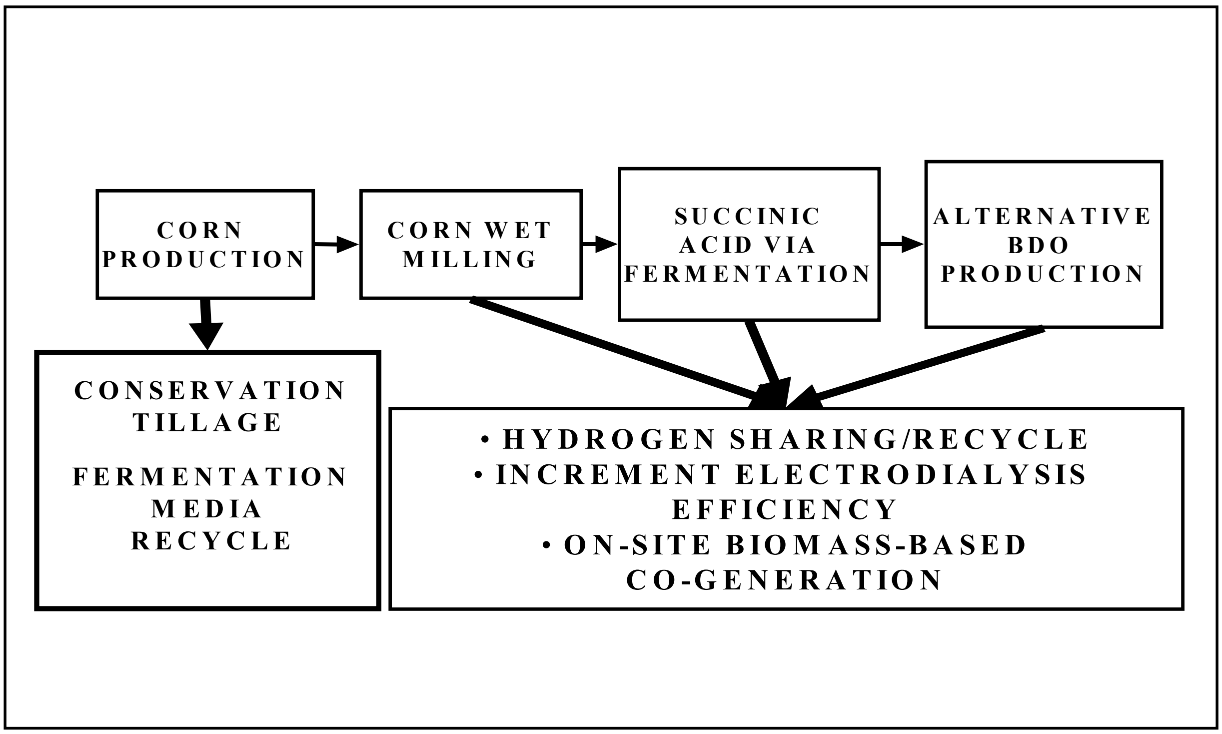


Table 5.2

Production of 1,4-Butanediol
Summary LCI

	Emissions and Consumption (lb/lb BDO)									
	Conventional Process					Alternative Process				
	Trunk		BDO			Trunk		BDO		
Component	**Processes**	**Energy**	**Process**	**Energy**	**Total**	**Processes**	**Energy**	**Process**	**Energy**	**Total**
Air Emissions										
Nox	1.93E-04	5.85E-04		7.11E-03	7.89E-03	3.60E-04	3.92E-03	0	1.47E-02	1.90E-02
PM-10		3.82E-06		5.80E-05	6.18E-05	1.11E-02	1.01E-03	0	1.80E-03	1.39E-02
CO	7.60E-05	1.31E-04	2.17E-03	8.92E-04	3.27E-03	3.61E-04	6.13E-03	5.34E-03	5.10E-03	1.69E-02
CO2	2.59E-02	0.11	0.34	2.82	3.29	0.06	0.84	-0.74	3.13	3.30
Organic Compounds			1.29E-03		1.29E-03	1.85E-04	1.61E-06	3.16E-03		3.35E-03
Non-Methane VOC's		1.79E-06		2.85E-05	3.03E-05	7.33E-04	8.45E-06	0	4.66E-05	7.88E-04
Methane	2.43E-05			3.39E-05	5.82E-05	0	6.65E-06	0	8.27E-06	1.49E-05
N2O					0	4.84E-04	4.21E-04	0	7.29E-04	1.63E-03
MEA			1.38E-05		0			3.38E-05		3.38E-05
Total Particulate	7.75E-06	6.53E-05		1.47E-04	2.20E-04	9.29E-03	1.53E-03		1.35E-03	1.22E-02
HCL					0	1.12E-05	0			1.12E-05
Ammonia	5.96E-06	1.58E-08		2.29E-08	6.00E-06	4.49E-04	2.66E-08		3.29E-07	4.49E-04
Chlorine					0.00E+00	1.23E-06	0	8.36E-07		2.06E-06
Sulfuric Acid	1.84E-09				1.84E-09	7.57E-07	0			7.57E-07
Sox	3.30E-06	1.08E-03	7.93E-06	1.57E-03	2.65E-03	4.62E-04	3.63E-03	1.95E-05	2.52E-02	2.93E-02

Hydrocarbons	2.93E-04	3.51E-05		5.08E-05	3.79E-04	1.34E-05	3.92E-04		7.29E-04	1.13E-03
Aldehydes	1.70E-06	1.58E-08		2.29E-08	1.74E-06	1.48E-05	2.13E-06		3.29E-07	1.72E-05
Organic Acids	2.17E-06				2.17E-06		1.34E-06			1.34E-06
NO					0	2.26E-03				2.26E-03
Nitric Acid					0	6.21E-06	0			6.21E-06
Fluoride					0	5.64E-07	0			5.64E-07
Acid Mist					0	3.18E-05	0			3.18E-05
Alachlor					0	3.17E-05				3.17E-05
Atrazine					0	5.85E-05				5.85E-05
Metalachlor					0	3.88E-05				3.88E-05
Cyanazine					0	3.03E-05				3.03E-05
Fonofos					0	4.69E-06				4.69E-06
Turbufos					0	1.24E-05				1.24E-05
Chlorpyrifos					0	8.07E-06				8.07E-06
Lead		2.10E-07		3.04E-07	5.14E-07		3.53E-07		4.36E-06	4.71E-06
Mercury					0			1.07E-07		1.07E-07
Acetylene			4.61E-05		4.61E-05					0
Kerosene		1.62E-07		2.35E-07	3.97E-07		2.73E-07		3.37E-06	3.64E-06
Formaldehyde	1.54E-05		5.70E-05		7.24E-05					0
Hydrogen			0.00E+00		0					0
Nitrogen			3.14E-02		3.14E-02					0
Copper	2.65E-08		2.26E-06		2.28E-06					0
Nickel	2.65E-08		1.11E-08		3.76E-08					0
Rhodium			0.00E+00		0					0
Butyl alcohol	1.38E-09		3.10E-05		3.10E-05					0

Propionaldehyde			6.54E-06		6.54E-06					0
Acetone	7.37E-07		2.69E-05		2.76E-05					0
Toluene			8.06E-05		8.06E-05					0
Methanol	5.81E-05				5.81E-05					0
Zinc	2.65E-08				2.65E-08					0
SO2	2.28E-05				2.28E-05					0
Hexane	5.87E-06				5.87E-06					0
Heptane	7.56E-06				7.56E-06					0
Octane	5.05E-06				5.05E-06					0
C-7 cycloparaffins	1.06E-06				1.06E-06					0
C-8 cycloparaffins	3.89E-07				3.89E-07					0
Pentane	3.66E-06				3.66E-06					0
Ethane	4.19E-06				4.19E-06					0
Propane	6.57E-06				6.57E-06					0
n-Butane	5.20E-06				5.20E-06					0
iso-Butane	2.59E-07				2.59E-07					0
Benzene	6.49E-08				6.49E-08					0
Wastewater Emissions										
Wastewater	5.79E-01		8.36E-01		1.42E+00	7.87E+00		3.07E+01		3.86E+01
BOD5		1.58E-08		2.29E-08	3.88E-08	6.29E-04	2.66E-08	1.04E-03	3.29E-07	1.67E-03
Total Suspended Solids		3.45E-08		4.98E-08	8.43E-08	7.86E-04	5.79E-08	1.50E-03	7.15E-07	2.29E-03
Phosphorus					0	1.23E-04				1.23E-04
Potassium					0	5.10E-04				5.10E-04
Sodium	1.27E-03				1.27E-03			1.10E-02		1.10E-02
Choride					0			1.98E-02		1.98E-02

Chlorine						5.04E-08				5.04E-08
Ammonia					0	8.81E-06				8.81E-06
Alachlor					0	2.77E-07				2.77E-07
Atrazine					0	3.00E-06				3.00E-06
Metalachlor					0	1.22E-06				1.22E-06
Cyanazine					0	1.69E-06				1.69E-06
Fonofos					0	8.09E-08				8.09E-08
Turbufos					0	2.14E-07				2.14E-07
Chlorpyrifos					0	2.31E-07				2.31E-07
Nitrates (as nitrogen)					0	1.94E-03				1.94E-03
Sulfuric Acid		1.02E-04		1.48E-04	2.50E-04		1.72E-04		2.12E-03	2.30E-03
Iron		3.20E-04		4.63E-04	7.84E-04		5.38E-04		6.65E-03	7.19E-03
Dissolved Solids	6.05E-08	1.68E-05		2.43E-05	4.12E-05		2.83E-05		3.49E-04	3.77E-04
COD		7.11E-08		1.03E-07	1.74E-07		1.19E-07		1.48E-06	1.59E-06
Phenol		5.29E-09		7.65E-09	1.29E-08		8.88E-09		1.10E-07	1.19E-07
Sulfide		5.29E-09		7.65E-09	1.29E-08		8.88E-09		1.10E-07	1.19E-07
Oil and Grease	3.13E-05	1.06E-08		1.53E-08	3.13E-05		1.78E-08		2.20E-07	2.37E-07
Acid		1.06E-08		1.53E-08	2.59E-08		1.78E-08		2.20E-07	2.37E-07
Metals		5.29E-09		7.65E-09	1.29E-08		8.88E-09		1.10E-07	1.19E-07
Formaldehyde			2.98E-05		2.98E-05					0
Acetylene			1.81E-05		1.81E-05					0
Copper	1.70E-09		1.34E-06		1.34E-06					0
Nickel	2.12E-09		7.70E-07		7.72E-07					0
Butyl alcohol			1.10E-05		1.10E-05					0
Zinc	3.03E-09				3.03E-09					0

Wastewater Reinjected	2.06E+00				2.06E+00					0
Wastewater Injected	2.98E-01				2.98E-01					0
Arsenic	2.61E-09				2.61E-09					0
Benzene	6.28E-08				6.28E-08					0
Boron	1.34E-06				1.34E-06					0
Chloride	1.00E-03				1.00E-03					0
Mobile Ions	3.07E-03				3.07E-03					0
Cadmium	2.14E-08				2.14E-08					0
Chromium	1.94E-09				1.94E-09					0
Mercury	4.88E-10				4.88E-10					0
Thallium	4.61E-10				4.61E-10					0
Solid Wastes										
Resins and membranes					0			1.00E-03		1.00E-03
Sludge					0			2.75E-01		2.75E-01
HCL					0	1.73E-07				1.73E-07
Ammonia					0	2.83E-07				2.83E-07
Coal Ash					0	2.01E-02				2.01E-02
Fly Ash		3.08E-03		4.46E-03	7.54E-03		5.18E-03		6.40E-02	6.92E-02
Bottom Ash		9.18E-04		1.33E-03	2.25E-03		1.54E-03		1.91E-02	2.06E-02
Slag		4.02E-04		5.82E-04	9.84E-04		6.75E-04		8.35E-03	9.02E-03
FGD Solids		1.31E-03		1.90E-03	3.21E-03		2.21E-03		2.73E-02	2.95E-02
Depleted Uranium		2.30E-04		3.33E-04	5.63E-04		3.86E-04		4.78E-03	5.16E-03
Mining Residues	4.54E-07	1.46E-02		2.12E-02	3.58E-02		2.46E-02		3.04E-01	3.28E-01
U238		9.61E-07		1.39E-06	2.35E-06		1.61E-06		1.99E-05	2.16E-05
U236		6.35E-10		9.18E-10	1.55E-09		1.07E-09		1.32E-08	1.42E-08

U235		8.09E-09		1.17E-08	1.98E-08		1.36E-08		1.68E-07	1.82E-07
Pu (fissile)		6.58E-09		9.51E-09	1.61E-08		1.10E-08		1.36E-07	1.48E-07
Pu (nonfissile)		2.53E-09		3.66E-09	6.19E-09		4.25E-09		5.25E-08	5.67E-08
Fission Products		4.60E-09		6.65E-09	1.13E-08		7.73E-09		9.55E-08	1.03E-07
Acetylene			3.16E-04		3.16E-04					0
Formaldehyde			7.41E-04		7.41E-04					0
Copper	1.33E-08		1.15E-05		1.15E-05					0
Nickel			1.21E-06		1.21E-06					0
Butyl alcohol			0.00E+00		0.00E+00					0
Cupriene polymers			8.91E-04		8.91E-04					0
Propionaldehyde			2.31E-05		2.31E-05					0
Acetone			6.49E-05		6.49E-05					0
Toluene			1.32E-02		1.32E-02					0
3-hydroxy-2-methylpropional			5.24E-05		5.24E-05					0
4-hydroxybutyrate			1.09E-04		1.09E-04					0
Methanol	1.33E-08				1.33E-08					0
Resource Consumption										
Coal		4.95E-02		7.15E-02	1.21E-01		2.21E-01		1.25E+00	1.47E+00
Natural Gas	7.10E-01	7.57E-02	1.68E-01	7.22E-01	1.68E+00		8.82E-02		4.54E-01	5.42E-01
LPG					0		7.41E-03			7.41E-03
Petroleum	7.46E-03	2.81E-04		4.06E-04	8.15E-03		3.59E-02		5.48E-03	4.14E-02
Electricity		7.27E-08		1.05E-07	1.78E-07		1.22E-07		1.51E-06	1.63E-06
Sulfur					0	1.37E-02				1.37E-02
Phosphate Rock					0	3.94E-02				3.94E-02
Potassium Chloride					0	1.15E-02				1.15E-02

Soil					0	3.03				3.03
Water	8.38E-02		49.64		49.73	11.51		71.92		83.43
Uranium		7.38E-07		1.07E-06	1.80E-06		1.24E-06		1.53E-05	1.65E-05
Hydropotential		2.72		3.93	6.65		4.57		56.45	61.01
Hydrogen			4.89E-02		4.89E-02				1.20E-01	1.20E-01
Propylene oxide			7.58E-02		7.58E-02					0
CO			3.41E-02		3.41E-02					0
Copper			2.04E-04		2.04E-04					0
Nickel			2.14E-04		2.14E-04					0
Toluene			1.33E-02		1.33E-02					0
n-Methylpyrolidinone	3.32E-04				3.32E-04					0
Land Use	6.31E-07				6.31E-07	1.30E-04				1.30E-04
Energy Consumption										
Coal		594		858	1,452		2,435		13,770	16,205
Natural Gas	16,730	1,786	4,150	17,032	39,698		2,184	0	11,250	13,434
LPG					0		812			812
Uranium		154		223	377		259		3,196	3,454
Hydroelectric		51		74	125		86		1,060	1,145
Petroleum	143	5		8	156		688		105	793
Geothermal		5		7	11		8		93	101
Total	16,873	2,594	4,150	18,201	41,818		6,471		29,474	35,945

Table 5.3. Comparison of Raw (Unweighted) Impact Scores by Criteria for the Convention versus Alternative Feedstock BDO Process[a]

Impact Category	CF Process	AF Process
Ozone Depletion	0	0
Global Warming	3.29	3.30[b]
Resource Depletion	607	**293**
Acid Rain	**1.3E-02**	2.7E-01
Smog	**2.1E-03**	3.1E-03
Water Use	**49.73**	83.43
PM10	**6.2E-05**	1.4E-02
Human Inhalation Toxicity	**1.4E-01**	5.0E-01
Carcinogenicity	4.3E-04	**2.7E-07**
Solid Waste Disposal/Land Use	**8.1E-06**	4.3E-04
Resource Extraction/Production Land Use	**6.3E-07**	1.3E-04
Terrestrial (wildlife) Toxicity	**1.2E-02**	1.6E-02
Aquatic (fish) Toxicity	**5.6E-03**	3.7E-02
Eutrophication	1.7E-02	2.0E-02

[a] Bold score values indicate the preferred option.

[b] Scores differing by less than 25% are not significantly different.

Table 5.4 Summary Results of Detailed LCA for BDO Process Development

Option	Environmental Characteristics
Conventional Route	♦ Coal is the resource material most heavily used in the conventional process life cycle.
	♦ Energy requirements for the life cycle are met by fuels using electricity generation, steam generation for motive power and process heating, and transportation.
	♦ Methanol and formaldehyde are the largest hazardous airborne releases from the processes preceding BDO manufacturing. Butyl alcohol and acetone are the largest releases from the BDO manufacturing step.
	♦ The carcinogenicity and resource depletion environmental impact categories have greater normalized impact scores than those for the alternative process.
	♦ The conventional and alternative processes are indistinguishable with regard to their global warming potential contributions.
Alternative Route	♦ Natural gas is the resource material most heavily used in the alternative process life cycle.
	♦ Energy requirements for the life cycle are met by fuels using electricity generation, steam generation for motive power and process heating, and transportation.
	• The acid rain, smog, water use, pm10, human inhalation toxicity, solid waste disposal/land use, resource extraction/production land use, and aquatic (fish) toxicity impacts scores for the alternative process are greater than those for the conventional process.